THE USE OF ADCPS TO MEASURE TURBULENCE AND SPM IN SHELF SEAS.

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Abstract: *In recent years the use of Acoustic Doppler Current Profilers (ADCPs) to estimate Reynolds stresses, using the so called variance method, has become popular; we have spent quite some time in validating this method using independent measurements. This work reports on the comparison of ADCP and Current Velocimeter (ADV) estimates of Reynolds stresses. The comparison of the ADCP and ADV is encouraging during periods when no strong waves were present with both the explained variance of 0.8 and the slope of the regression being 0.97. Once we can trust the Reynolds stress estimates we can then use them to calculate bottom drag coefficients and in combination with the vertical shear the turbulence production (P) and eddy viscosity (N_z). Recently the use of the structure function method, borrowed from meteorology, has shown promising results in estimating turbulence dissipation (ε), so that we have an almost complete balance of the Turbulent Kinetic Energy (TKE). The ADCPs have become one of the most versatile instruments in shelf sea oceanography, they do not only allow to measure currents and produce estimates of turbulence as explained above, but we can also estimate Suspended Particulate Matter (SPM) from the acoustic backscatter and directional wave spectra using different methods.*

Keywords: *Turbulence, ADCP, Reynolds stress, Variance method, Structure function, SPM.*

1. INTRO DUCTION

To be able to model the water column structure momentum and SPM it is necessary for numerical models to have an accurate representation of the vertical transfers due to turbulent diffusion. For this modern numerical models use turbulence closure schemes which allow non-linear interactions between shear production and buoyancy fluxes. Most of these closure schemes involve explicit representations of the evolution of turbulent kinetic energy (TKE) [1] including its production due to shear stress and buoyancy and its dissipation through which energy is converted to heat. Until recently testing these turbulence closure schemes with field data was not possible, but with developments to observing technologies measurements of turbulent parameters can now be made in the field, e.g. turbulence dissipation [2] and turbulence production [3]. This new capability should help realization of a better understanding and representation of turbulent processes.

In the quest to measure turbulence parameters the use of Acoustic Doppler Current Profilers (ADCPs) to estimate Reynolds stresses and TKE production (P) has become common practice in recent years [3], [4], [5]. Great effort has been put into studying the theoretical errors of the method [6], and to achieve a clear validation by comparing ADCP Reynolds stresses with estimates from other instrumentation [7],[8]. So that we can now have some confidence in the TKE production estimates. More recently Wiles et al [9] has been using the structure function method to estimate the TKE dissipation (ε), producing promising results, although the dissipation values appear to be slightly under estimated.

The advantage of the ADCP is its simplicity and versatility. The instrument is simple to set and use and will allow you to have a full water column estimate of P, ε and SPM, and if it setup properly will also let you have a directional wave spectra.

2. METHODS

2.1. The variance method to estimate P

The ADCP variance method to calculate Reynolds stresses is relatively simple and cheap, since bottom mounted ADCPs can be left for long deployments, in comparison with the use of shear profilers which need to have a ship present all the time. The Reynolds stresses are calculated following the variance method first explained by Lohrmann *et al.* [10] and applied by Stacey *et al.* [4], and Rippeth *et al.* [3]. The method is based on the fact that an ADCP has two pairs of opposing acoustic beams, and that each beam measures a velocity that is actually a weighted sum of the local horizontal and vertical velocities. For example, if we choose beams 3 and 4 as one set of opposing beams, it follows that the velocities determined for beams 3 and 4 (u_3 and u_4) are given by:

$$u_1 = v\sin\theta + w\cos\theta\ ; \quad u_2 = -v\sin\theta + w\cos\theta$$
$$u_3 = u\sin\theta + w\cos\theta\ ; \quad u_4 = -u\sin\theta + w\cos\theta \tag{1}$$

where θ is the angle of the acoustic beam from the vertical (20° in this case) and u, v and w are the horizontal and vertical velocity components. Separating the velocities into mean and fluctuating quantities and taking the difference between the two opposing beams it can be shown by combining the equation (1) and ensemble average them that

$$\overline{u'w'} = \frac{\overline{{u_3}'^2} - \overline{{u_4}'^2}}{4 sin\theta\, cos\theta} \qquad and \qquad \overline{v'w'} = \frac{\overline{{u_1}'^2} - \overline{{u_2}'^2}}{4 sin\theta\, cos\theta} \tag{2}$$

where the overbars indicates the temporal means and primes indicate temporal fluctuations. The rate of production of TKE (P), in W m^{-3} is estimated from the product of the Reynolds stresses and the velocity shear according to:

$$P = -\rho\left(\overline{u'w'}\frac{\partial \bar{u}}{\partial z} + \overline{v'w'}\frac{\partial \bar{v}}{\partial z}\right) \tag{3}$$

where ρ is the water density and z is the vertical coordinate. Using this method we can also estimate the value of eddy viscosity, N_z, as:

$$\frac{\tau_x}{\rho} = N_z\frac{\partial u}{\partial z} = \overline{u'w'} \qquad and \qquad \frac{\tau_y}{\rho} = N_z\frac{\partial v}{\partial z} = \overline{v'w'} \tag{4}$$

where τ_x and τ_y are the eastward and northward components of stress. For a more detailed explanation of the variance method, refer to [3] and [4].

The ADV follows a direct method of measuring the Reynolds stresses which involves rapid sampling of the three components of velocity in a small sampling volume, so that terms of the type $\overline{u'w'}$ can be calculated directly from the covariance of u and w. This approached was pioneered by Bowden and Fairbairn [11], using electro-magnetic current meters. In recent years the use of ECMs has been substituted by using ADVs, which are simpler to use and can sample smaller water volumes, depending on frequency and brand. The ADVs used in these measurements were Sontek 5 MHz Ocean instruments which have a volume sample of about 2 cm^3 at sampling rates of about 25 Hz,. These instruments are highly accurate (long term error of the order of 3×10^{-6} m^2 s^{-2}) and have become the standard for boundary studies in the laboratory and field experiments.

2.2. The structure function method to estimate ε.

The method was first developed by meteorologist to estimate ε from radar measurements [12] and it has been applied to the marine environment, with promising results, by Wiles [9]. The method is based on the theory that a second order structure function *D(z,r)* can be defined as:

$$D(z,r) = \overline{(v'(z) - v'(z+r))^2} \tag{5}$$

D(z,r) is the mean-square of the along beam velocity fluctuation (*v'*) difference between two point separated by a distance *r*. If we use the Taylor cascade theory to relate length scales and velocity scales to isotropic eddies we have:

$$D(z,r) = C_v^2\varepsilon^{2/3}r^{2/3} \tag{6}$$

where C_v^2 is a constant between 2 and 2.2 for atmospheric studies, we will use this assumption for marine studies, although it appears to underestimate the dissipation values.

2.3. SPM estimates.

The ADCP is a system with four different acoustic transducers and as such each transducer can be used as an acoustic back scatter system (ABS) and be used to calculate the SPM concentration. Unfortunately the acoustic backscatter signal is recorded as counts in the ADCP instrument and to convert from counts to decibels (dB) we have to use the following sonar equation:

$$S_v = C + 10\log_{10}((T + 273.16)R^2) - L_{DBM} - P_{DBW} + 2\alpha R + K_c(E - E_r) \tag{7}$$

where Sv is the backscatter strength; C is a constant ~-129.1; T is temperature in °C R is the cell range in m; L_{DBM} and P_{DBM} are the transmit pulse in m and the transmit power in W; α is the absortion coefficient of water (dBm^{-1}) ~0.48; E_r the echo intensity when no signal ~40; E Echo intencity, K_c is the conversion factor from counts to dB wit typical values about 0.45 dB/count [13]. The typical way of converting the acoustic backscatter data into SPM is to regress the values against bottle or pump samples or other estimates of SPM. In the case of the Gulf of California the corrected signal strength from the four beams was averaged; these data were then calibrated using vertical SPM profiles collected every half hour during 28 May 2002 using an Optical Backscatter System (OBS), which was calibrated with water samples. The linear regression between SPM concentration and acoustic backscatter produced the following relation:

$$10\,log_{10} C = 21 + 0.25B, \tag{8}$$

where C is the SPM concentration in g m^{-3} and B is the acoustic backscatter signal in dB. This backscatter-concentration regression explains almost 86% of the variance.

3. OBSERVATIONS.

As part of the Proudman Oceanographic Laboratory (POL) science programme and within other projects we have been carrying out measurements of Reynolds stresses in several shelf seas and estuaries, some of them include: North Sea, Irish Sea, Gulf of California, the Dee Estuary in the UK and San Quintin Bay in Mexico. The observations presented here will be mainly from Liverpool Bay in the Irish Sea where POL has its coastal observatory and from the Gulf of California, where we have got some of the best data up to date.

In Liverpool Bay a 1.2 MHz ADCP was deployed from 23 between January to 6 March 2003 in about 22m of water. The ADCPs was operated using RDI rapid sampling mode 12 and set to record 8 subpings per 1 second ensemble with a 0.5m bin. The ADV was a 5 MHz Sontek Ocean Hydra system which was set to sample at 25 Hz. The instruments were mounted on the same bottom frame about 1.5 m apart, with the ADV mounted upwards on an arm about 0.85 m away from the frame to avoid any turbulent effect due to the frame; the data were recorded for 10 minutes every hour. This was to allow for the 40 day deployment. The measuring volume of the ADV and the centre of the second ADCP bin were co-located at about 1.5 m from the seabed. (At these heights the ADCP bins are about 0.7 m apart in the horizontal, for a 20º beam angle). In the Gulf of California we only deployed a 1.2 MHz ADCP during the spring tidal period, between 27 and 29 May 2002 in a mean water depth of about 25 m, which is within the mixed region of the Upper Gulf of California, the ADCP recorded data continuously and was operated in mode 1 set to record a 6 acoustic ping average every 2 seconds.

Both the fast sample ADCP and current meter records were analyzed with a basic averaging period of 10 minutes. Values of Reynolds stresses are given in units of m^2 s^{-2} and should be multiplied by the water density (~1027 kg m^{-3}) for conversion to Pascals. For display purposes the data were rotated so that the $\overline{u'w'}$ component of the Reynolds stress was aligned with the major axis of the barotropic tidal current, which will be called the along-stream component, while $\overline{v'w'}$ will be the across-stream component. For quantitative comparison purposes the ADCP and ADV data were considered as vectors and compared using complex linear regression.

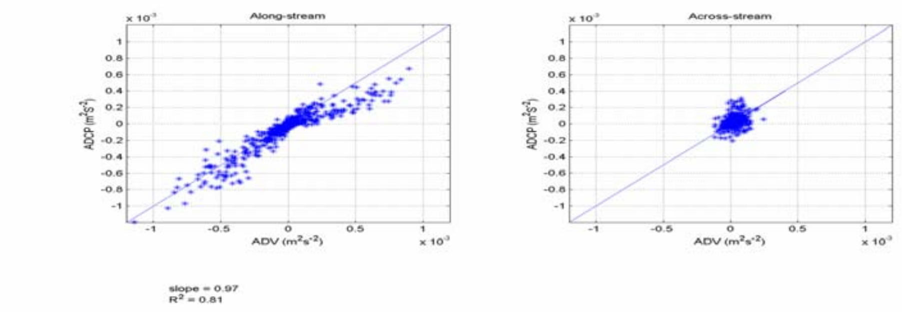

Fig.1: Scatter plot ADCP vs ADV estimates of along stream and across stream Reynolds stress, for calm weather period in Livepool Bay from 8 February to 5 March 2003.

Scatter plots of the Reynolds stress estimates from Liverpool bay, using the second ADCP bin against ADV estimates during a period of calm sea, wave height less than 1 m and periods of about 2 seconds, are shown in fig. 1. The explained variance (R^2) is 0.81 and the slope is 0.97 with an intercept of 4 × 10^{-5} m^2 s^{-2} when the ADCP estimates are regressed against the ADV. Fig. 2 shows the time series of Reynolds stresses for the regression used in figure 1. The along stream component of the Reynolds stress appears to be in good agreement between ADCP and ADV, while there appears to be clear over estimation of the across stream component of up to 2 × 10^{-4} m^2 s^{-2}. There is in this case, however, a repeatable, since we have made measurements at this site more than once showing the same pattern, an unexplained reduction of the slope of the correlation on flood tides, that we have not seen at other sites. What could cause a reduction in the turbulent length scale such that the ADCP-based estimate is reduced on flood tides? Two possibilities are an effect of stratification or possibly of asymmetric bedforms in predominantly sandy sediment. The site is near the mouth of the river Mersey. For this deployment the water column was always well mixed at high water and also for more than half the tides at low water. For the remainder it was weakly stratified at low water, generally by less than 0.5 kg m^{-3} but on seven tides by 1 kg m^{-3}, this switching between mixed and weakly stratified should be caused by tidal straining, which could bring an extra production term due to convection and somehow be observed by the ADCP. The third possibility (the frame or instruments affecting the flow) is unlikely since the same pattern has been seen on several deployments.

During the observational period, the tidal velocities were almost rectilinear with a semi-major axis of the order of 0.6 m s^{-1} near the sea surface and 0.3 m s^{-1} near bottom, while the near bottom and near surface tidal shears were 0.03 and 0.01 s^{-1}, respectively.

The data from the Gulf of California is plotted in Fig. 3. with ε (a), P (b) and SPM (As expected, the highest rate of TKE production is found near the bed with values decreasing about an order of magnitude between the bottom and 12 mab (Fig. 3b). The near-bed (~1.5 mab) maximum P is of the order of 10^{-2} W m^{-3} during both ebb and flood with minimum values at slack water of the order of 10^{-4} W m^{-3}. The bottom production P shows a quarter-diurnal periodicity as it is dependent on the current speed, *i.e.* there are two maxima of current speed per semi-diurnal tidal cycle. As is the case for the Reynolds stresses, there is an apparent asymmetry between flood and ebb, with higher values of P and greater extension up into the water column during ebb.

Similar to TKE production, the concentration of SPM (fig. 3c) shows a quarter-diurnal variability with maxima of more than 30 g m^{-3} near the bottom, decreasing to less than 10 gm^{-3} at about 12 mab. The SPM concentration also appears to have a similar asymmetry in the near bottom region, but there is no sign of the near-surface localized maxima observed for P at low water.

Estimates of eddy viscosity (N_z) were calculated from hourly averages of Reynolds stresses and shear following equation (4). These estimates of eddy viscosity (fig. 4a) show variability between 10^{-3} and 10^{-2} m^2 s^{-1} in the bottom half of the water column, with maximum values around peak flow and low values around slack water. We also estimated the eddy viscosity from the regression of all the estimates of Reynolds stress and shear (figure 4b); this is equivalent to the mean vertical profile of N_z. The mean eddy viscosity shows a typical profile with values slightly increasing from the bottom (~ 3×10^{-3} m^2 s^{-1}) to about 3.8×10^{-3} m^2 s^{-1} at about 3 mab followed by a continuous decrease to near zero at 12 mab.

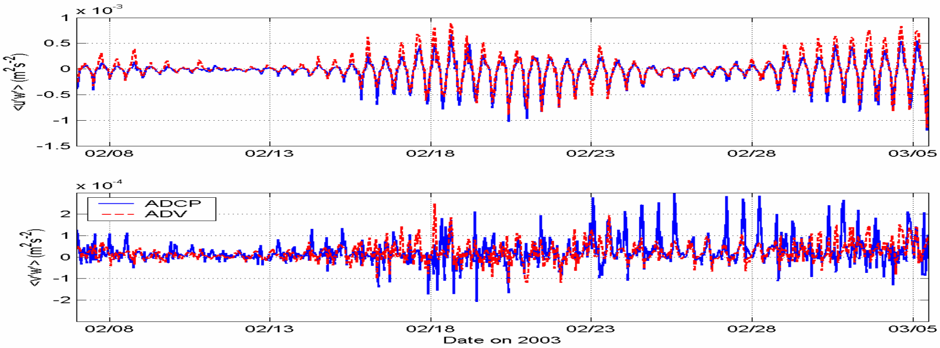

Fig.2: Time series of Reynolds stresses from 8 February to 5 March 2003, (_) ADCP, (--) ADV, from Liverpool Bay. Note the different scales on the along- and cross-stream diagrams.

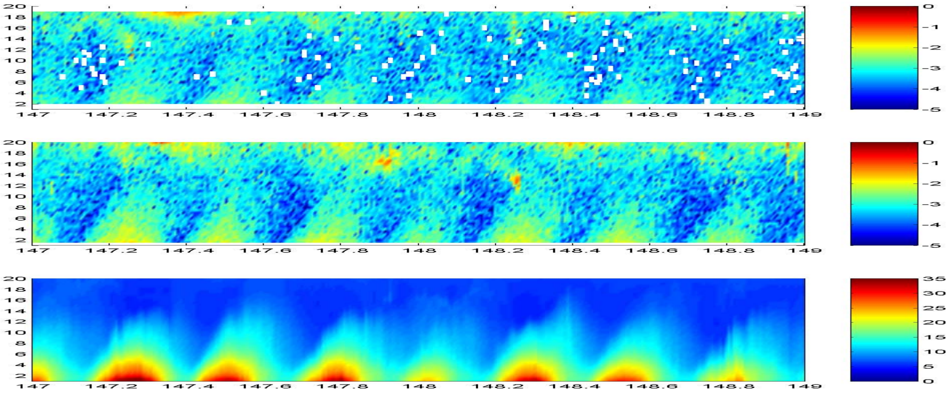

Fig.3: Time series of TKE dissipation (ε) and Production (P)in $\log_{10}(Wm^{-3})$ and SPM in gm^{-3}

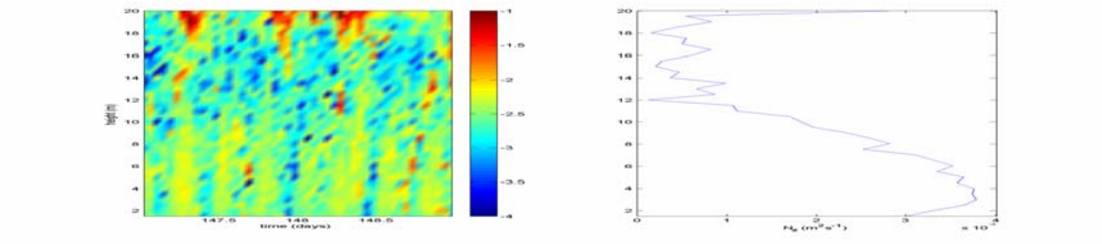

Fig.4: Estimates of eddy viscosity N_z (m^2S^{-1}) a) time series; b) temporal average

4. DISCUSSION AND CONCLSION.

This study together with [7] and [8], builds confidence on the use of ADCP Reynolds stress estimates in shelf seas at least during periods of calm weather. Nevertheless it should raise awareness that in the presence of waves the methods break down, so that we should be very careful when interpreting the data. A useful guide if co-located ADV measurements are not available is to compare the ADCP estimates of Reynolds stress against a quadratic drag law, u|u|. The fact tha we can use estimates of Reynolds stresses allow us to do some interesting work, like in the case of the Gulf of California, where we show some good coherence between the TKE production and dissipation with the SPM.

This work advances the understanding of turbulence generation and dissipation and SPM dynamics by:

1) Demonstrating the capability to continuously and simultaneously measure TKE production, dissipation and SPM using a single instrument, combining the variance method [3],[4] , the structure function method [12] and acoustic backscatter measurements to estimate SPM.
2) Illustrating good agreement between these observations and classical theoretical studies of turbulence and SPM [14].

To our knowledge, this is the first complete data set that combines measurements of turbulence characteristics, such as TKE production, dissipation and Reynolds stresses, and SPM concentrations in shelf seas. As such, it offers simple and exciting opportunities, applicable in a wide range of conditions, to test and develop turbulence and SPM models and thereby improve our predictive capabilities.

5. ACKNOWLEDGEMENTS.

This work was partially funded by the UK NERC grant NER/M/S/2002/00076, ONRIFO VSP grant N00014-02-1-4031 and POL's core science budget.

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